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Predicting Performance of Large-Diameter Buried Flexible Pipes: Learning from Case Histories

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SYNOPSIS: Analytical approaches to predicting pipe deflections are based on the predetermined pipe properties, the anticipated soil properties and on the assumption that the specified installation configuration can be met. However, in-place pipe deflections do often deviate from the predicted. This paper summarizes the observations made from more than twenty case histories of entrenched large-diameter flexible high density polyethylene pipes and discusses the effects of construction methods and site conditions on pipe performance. Procedures are also presented on how site conditions and construction methods can be accounted for when using the TAMPIPE (Texas A&M PIPE) method and the Spangler's method. Procedures are given for predicting the variability of pipe deflections in the field. The TAMPIPE method is also shown to be accurate in predicting the long-term deflection of the pipe.

INTRODUCTION

Analytical methods of designing large-diameter buried pipes invariably assume that the pipe can be installed according to specifications, without considering the difficulties posed by the actual site condition. For example, providing a vertical trench wall in a loose soil or attempting to achieve specified compaction in a flooded trench are both difficult. This paper attempts to introduce such considerations into the design process in order to bridge the gap between the theoretical and the practical.

THEORETICAL PREDICTIONS

The Spangler's equation (Spangler, 1951) which is a semi-empirical solution, has been the most popular method used in the design of buried flexible pipes for the past several decades. In recent years, the emphasis has been to formulate mechanistic solutions. The TAMPIPE [Texas A&M PIPE] solution (Chua and Lytton, 1987a) which will be considered here is one such method. This is an analytical regression-type solution developed using results obtained from a nonlinear finite element program called CANDE [Culvert ANalysis and DEsign] (Katona et.al., 1976). This procedure will compute the pipe vertical deflection, and the pipe maximum stress and strain for any given time period.

Spangler's Method

The Spangler's equation (also known as the Iowa Formula) is as follows:

$$\Delta D/D = \frac{D_l \; KW}{8E_pI_p/D^3 + 0.061\,E'} \qquad (1)$$

where: $\Delta D/D$ = pipe horizontal deflection (normally assumed to be the same as the vertical),
D_l = time lag factor,
K = bedding constant (0.083 - 0.11),
W = load per unit length of pipe (lb/linear inch)
E_p = the pipe elastic modulus (psi),
I_p = moment of inertia of the pipe wall (in^4),
D = pipe diameter (ins), and
E' = modulus of soil reaction (psi).

TAMPIPE Method

The TAMPIPE procedure considers a pipe buried in a trench of any width, and surrounded by three soil zones - the embedment (or bedding), the backfill and the in situ soils. Figure 1 shows a typical trench condition.

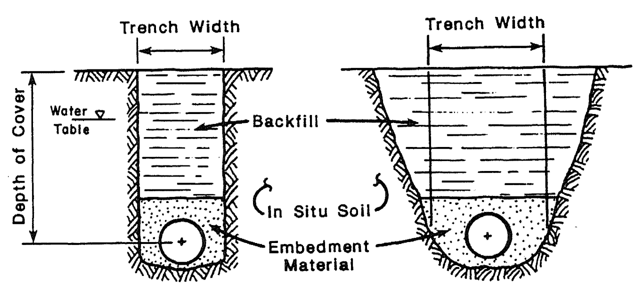

Figure 1. Trench Configurations

The pipe vertical deflection is given by:

$$\Delta D/D = \frac{B_f(1-A_f)\;\gamma z\;(1-W_f)}{8E_pI_p/(1-\nu_p)D^3 + C_f\,E_1'} \qquad (2)$$

where: B_f = bedding factor (function of Poisson's ratio of soil),
A_f = arching factor ,
γ = unit weight of soil,
ν_p = Poisson's ratio of pipe material,
C_f = a coefficient (function of Poisson's ratio of soil),
W_f = a factor to include the effects of a water table. and
E_1' = soil support modulus (psi).

The initial tangent modulus of the soil modeled by TAMPIPE (similar to CANDE) is given by,

$$E_i = K\ Pa\ (\ \sigma_3\ /Pa)\ ^n \qquad (3)$$

where: K_i = soil modulus number,
n = modulus exponent,
Pa = atmospheric pressure, and
σ_3 = the minor principal stress.

In view of this, the TAMPIPE procedure will require K_e, K_i and K_b which represent the embedment soil, in situ soil and the backfill soil, respectively. The soil support modulus E_1', which is a tangent modulus is calculated for the soil at the springline.

The time-dependent predictions made with TAMPIPE consider pipe material and the three soils to be viscoelastic. For the detailed development of the TAMPIPE procedure, refer to (Chua, 1986; Chua and Lytton, 1987b).

A REVIEW OF CONSTRUCTION PRACTICE

Twenty eight projects were selected from a period of time to form the basis of this study. These projects are representative of the practice with large-diameter high density polyethylene profile wall pipes. The pertinent characteristics of each of the installations are summarized in Table 1 which will be referred to in the following sections. In the case where multiple pipe sizes were used at different depths, only one representative size and depth was chosen and considered in the analysis.

Field Measurements

Pipe deflection ($\Delta D/D$) was determined by measuring the change in vertical diameter ($\Delta D/D$) due to earth and live loading. Typically, two to four measurements were taken per 20 ft pipe length with the total number of data points per project ranging from 50 to several hundreds. Probability plots of diametrical measurements approached a straight line, indicating that the standard deviation assumes a normal distribution. In order to compare projects, the coefficient of variation which is the ratio of the standard deviation to the mean is used. Figure 2 shows the mean pipe vertical deflections as well as the plus one and minus one standard deviation obtained for the various projects.

Installation Configuration

Pipe diameters considered ranges 18" to 72". The pipe stiffness (defined as $8E_pI_p/0.149\ D^3$) considered ranges from 5.4 psi to 49 psi. A trench width to diameter ratio of between 1.25 to 1.5 is usually called for in a design, but as can be seen, over-excavation is not uncommon. Depths of cover (measured from the ground surface to the spring line) considered here range up to 35 ft. Flexible plastic pipes have been installed to depths of over 100 ft in fills.

The vertical and the sloping trench wall configuration is shown in Figure 1. A removable trench box is sometimes used during construction to support the soil in order to keep the trench wall vertical. Column 12 shows whether open, sheeting or braced trench construction was carried out.

Table 1. Project Descriptions

PROJECT NUMBER	DIAMETER (INS)	P.STIFFN. (PSI)	COVER DEPTH (FT)	<---- TRENCH WIDTH ------> NO. DIA.	<---- WALL -----> TYPE	FIRMNESS	GROUND WATER	<-- EMBEDMENT --> TYPE	COMPACT. METHOD	IN SITU SOIL	CONSTR. TECHN.	INSPECT. (%TIME)	AVE.DEFL. (%)	STD.DEV.	COEF.VAR. (%)	TIME (DAYS)
COL.1	COL.2	COL.3	COL.4	COL.5	COL.6	COL.7	COL.8	COL.9	COL.10	COL.11	COL.12	COL.13	COL.14	COL.15	COL.16	COL.17
1	36	15.2	25	1.6	SLOPE	STIFF	NO	STONE	TAMP	MIXED	OPEN	100	1.6	1.3	81	1460
2	18	49	17	2		MEDIUM	NO	SAND	TAMP	SAND	OPEN	50	2.1	1.9	90	540
3	42	9.7	10	1.4	SLOPE	STIFF	NO	SAND	TAMP	MIXED	OPEN	100	1.7	1.1	65	90
4	42	52	35	1.4	VERT.	STIFF	NO	STONE	TAMP	SAND	OPEN	50	1	0.4	40	14
5	36	15.2	15.5	2		STIFF	YES	STONE	TAMP	SAND	OPEN	100	0.8	0.6	76	3
6	42	9.7	15.5	2	BOX	MEDIUM	NO	STONE	DUMP	CLAY/SILT	OPEN	0	2.5	1.4	59	780
7	36	15.2	15	1.7	SLOPE	V/LOOSE	NO	SAND	TAMP	CLAY/SILT	OPEN	0	0.9	0.9	100	3
8	48	6.5	11	1.8	SLOPE	V/LOOSE	YES	STONE	DUMP	CLAY/SILT	OPEN	FR	1.4	2.3	164	1
9	48	26	20	1.6	BOX	STIFF	DEWATER	STONE	SHOVEL	CLAY/SILT	BRACED	100	2	0.8	40	315
10	36	15.2	11.5	1.7	VERT.	MEDIUM	NO	GRAVEL	TAMP	MIXED	OPEN	50	2.3	1.1	48	730
11	54	18.4	12.5	1.6	BOX	STIFF	YES	CEM-SAND	TAMP	CLAY/SILT	SHEET	50	3.3	0.9	27	450
12	36	8.7	13.5	2.5	SLOPE	MEDIUM	YES	STONE	SHOVEL	CLAY/SILT	OPEN	50	4.1	1.7	41	150
13	54	7.3	20	1.3	SLOPE	STIFF	YES	STONE	DUMP	SAND	OPEN	50	4.2	2	48	300
14	60	5.4	11.5	2	BOX	V/LOOSE	DEWATER	STONE	TAMP	CLAY/SILT	SHEET	100	2.1	1	48	1095
15	24	32.5	13	3	BOX	V/LOOSE	YES	SHELL	TAMP	SAND	BRACED	50	1.5	1.9	127	365
16	18	49	7.5	2			(?)	CLAY(CH)	DUMP	CLAY/SILT	OPEN		5.4	2.8	52	300
17	30	25.9	20	2	BOX	V/LOOSE	DEWATER	MIXED	TAMP	SAND	BRACED	50	1.31	1	79	14
18	48	6.5	12	1.2		MEDIUM	YES	CEM-SAND	DUMP	CLAY/SILT	OPEN	FR	3.3	1.7	52	180
19	48	10.4	8	2	BOX	LOOSE	YES	STONE	DUMP	CLAY/SILT	BRACED	FR	3.5	1	29	1
20	36	8.7	12.5	1.7	BOX	V/LOOSE		STONE	DUMP	MIXED	BRACED	50	2.01	2.4	121	7
21	72	8	26	1.7	SLOPE	STIFF	NO	STONE	TAMP	SAND	OPEN	50	1.5	1	67	90
22	24	21.2	15	2	SLOPE	LOOSE	NO	STONE	TAMP	CLAY/SILT	OPEN	50	2.1	1.3	62	1
23	30	17.1	16	2.4	BOX	V/LOOSE	YES	SAND	TAMP	CLAY/SILT	BRACED	100	1.5	0.8	53	7
24	36	15.2	15	1.3		STIFF	NO	SAND	TAMP	CLAY/SILT	BRACED	50	2.2	2.1	95	1
25	36	24.2	10	1.7	SLOPE	V/LOOSE	YES	SAND	TAMP	CLAY/SILT	OPEN	100	0.31	0.3	97	1
26	24	15.9	17	2	SLOPE	MEDIUM	NO	STONE	TAMP	CLAY/SILT	OPEN	100	2.7	1.1	41	540
27	36	8.7	15	1.7	VERT.	STIFF	YES	STONE	SHOVEL	CLAY/SILT	OPEN	FR	2.49	1.2	48	90
28	24	21.2	6	2				STONE	SHOVEL	CLAY/SILT	OPEN		1.5	0.5	33	30
Footnotes:-					V/LOOSE for VERY LOOSE		DEWATER = YES	CEM-SAND =Cement-sand		MIXED implies SAND/CLAY/SILT		FR= Factory Representative				

Site Conditions

Column 7 describes the firmness of the site soil. The soil is classified as very loose, loose, and medium to stiff. For instance, a very loose soil indicate a collapsing trench if left open and unsupported. Column 9 shows whether a water table was encountered during construction and whether dewatering was done.

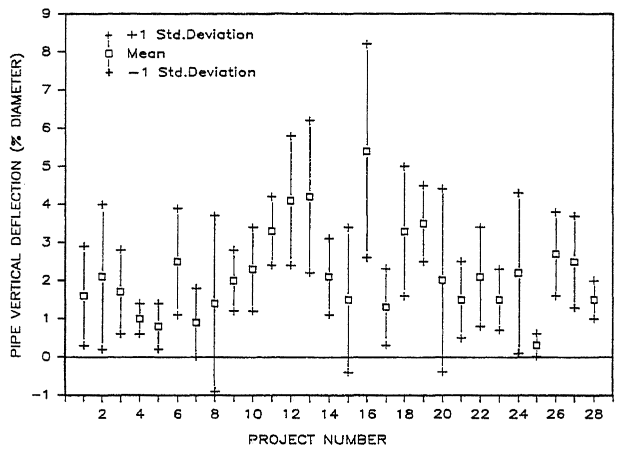

Figure 2. Observed Pipe Deflections and Variability

Embedment Materials

In about 50% of the projects, tamping was carried out to compact the embedment (bedding) materials. Shovel slicing accounts for 25%. However, for the rest of the projects, the embedment materials were simply dumped with no compaction. This practice should be discouraged since the highest deflections observed in this study were dumped embedment materials.

Embedment materials used include sand, crushed stone, pea-gravel, a mixture of sand and stone, and sea-shells. In one case, fat clay from the site itself was dumped around the pipe with no compaction. This resulted in a large pipe vertical deflection (Project 16).

Other Factors

From the measured pipe deflection shown in Table 1, it is evident that where there is good inspection, minimal deflections usually occur. The attitude of the contractor and the efficiency and quality of the construction equipment are important factors and should be considered. The variability of pipe deflection is probably an indicator of how conscientious the contractor is.

CONSTRUCTION CONSIDERATIONS

In developing the construction adjustments which may be required to more accurately predict the mean pipe vertical deflection, the philosophy is to attempt to explain the field data by modifying the design parameters affected rather than the common approach of simply using "add-on" deflections.

Figure 3 shows the pipe vertical deflections predicted using TAMPIPE and the Spangler's equation prior to adjusting for construction factors versus the observed values. The predictions made using Spangler's equation can be seen to be generally lower than the field measurements.

Upon reviewing the factors which may contribute to the difference between the predicted and the observed deflections, the most obvious cause is the condition of the trench. That is, whether it is a loose or wet or both and whether it is sloped (open cut) or braced. In a wet and loose trench, uncleaned wall sloughs and compaction difficulties may lead to increased deflections. These problems may be slightly compounded when a portable shield, or box, is used.

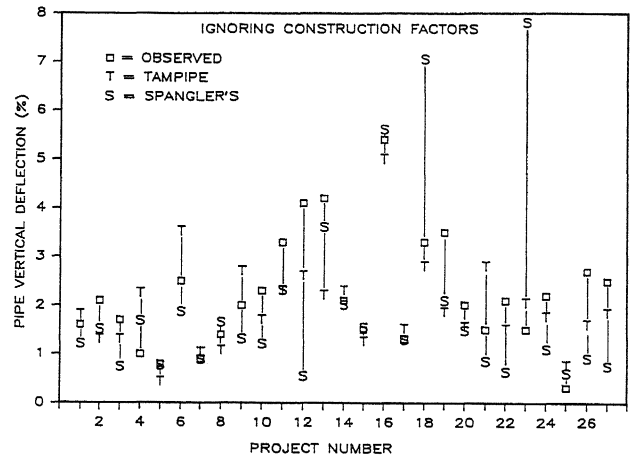

Figure 3. Initial Predictions of Pipe Deflections

Recommendations

TAMPIPE Method

From observations, it appears that the only adjustment required for TAMPIPE is in the modulus number of the embedment material, K_e. By reducing Ke, it was found that the TAMPIPE predictions can be improved to match the wet trench case, and the wet and unstable trench case. For cases in which remedial action such as dewatering of a wet trench, no reduction in K_e was required. Dewatering, when done properly, will allow the installation to be carried out as successfully as a dry one. The Ke-value can be multiplied by the factors shown in Table 2. These factors may be used in CANDE.

Table 2. Recommendations for TAMPIPE

Trench Condition	Reduction Factor
Stable and Wet Trench without dewatering	0.66
Unstable and Wet Trench without dewatering	0.5

Spangler's Method

The coefficients in the Spangler's equation were determined empirically from the field which may explain why the predictions are reasonable in most cases. The soil modulus used in the predictions (Figure 3) are shown in Table 3.

Table 3. USBR Values of the Soil Modulus E'

Soil Type	Compaction, % Proctor			
	Dumped	85	85-95	>90
Fine-Grained, CL, ML, ML-CL				
<25% coarse-grained	50	200	400	1000
>25% coarse-grained	100	400	1000	2000
Coarse-Grained, GW,GC,SM,SC				
>12% fines	100	400	1000	2000
<25% fines	200	1000	2000	3000
Crushed Rock	1000	3000	3000	3000

In order to enhance the accuracy of the predictions, the following recommendations are made.

Table 4. Additional Values of E' Values (psi) for Iowa Formula

Crushed Rock	
Dumped in wet in situ soil	500
Shovel sliced	
only under haunch	1000
in soft clayey in situ soil	500

Results

Figure 4 shows the predictions made using the TAMPIPE and the Spangler's equations after considering construction conditions.

PREDICTING THE VARIABILITY OF PIPE DEFLECTION FOR INDIVIDUAL PROJECT

The coefficient of variation for the each project can be estimated using the decision tree shown in Figure 5.

The standard deviation can be calculated from the coefficient of variation. The pipeline engineer can decide from standard deviation the number of pipe sections which will probably exceed the acceptable deflection. If the risk is unacceptable, the engineer can either (a) ensure that installation specifications are strictly followed, or (b) reduce the mean deflection by using a stiffer pipe or better embedment soil.

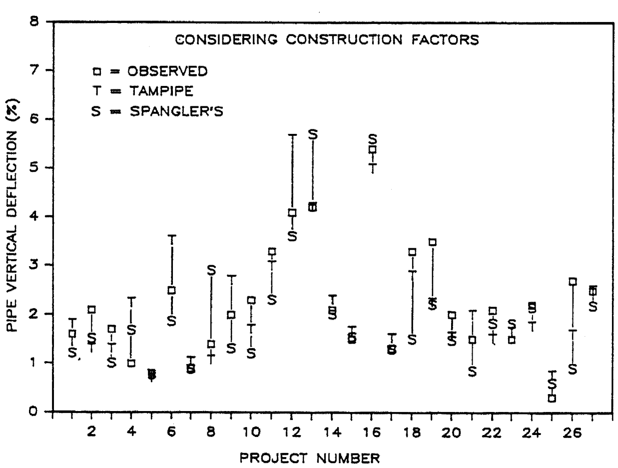

Figure 4. Final Prediction of Pipe Deflections

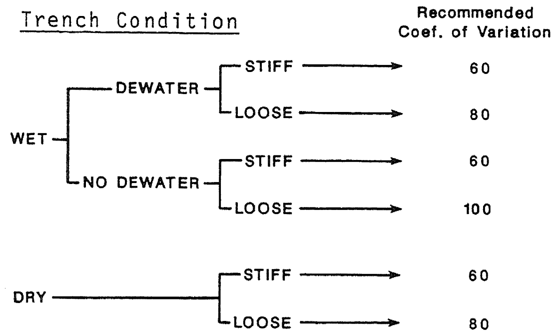

Figure 5. Determining Variability of Pipe Deflections

CONCLUDING REMARKS

Presented herein are case histories of projects involving large-diameter flexible buried pipe in which the mean pipe vertical deflections as well as the variability of the measurements are available. Procedures are presented in which input to the TAMPIPE and the Spangler's equation can be adjusted to reflect the construction methods as well as the site conditions during installation. A method of predicting the variability of the pipe deflections in the field is also presented.

Several factors causing in-place pipe deflections to deviate from the predicted were identified. The most critical factor involves the condition of the trench, namely, whether the trench wall is stable and whether a water table is present. It appears that appropriate remedial actions when effectively executed, such as using a trench box or dewatering, can still ensure a proper installation.

This study once again underscores the fact that proper construction procedure is just as important, if not more important, than an accurate design procedure.

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